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Astrophysics and Cosmology Confront the 17 keV Neutrino

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A host of astrophysical and cosmological arguments severely constrain the properties of a 17 keV Dirac neutrino. Such a neutrino must have interactions beyond those of the standard electroweak theory to reduce its cosmic abundance (through decay or annihilation) by a factor of 200. A predicament arises because the additional helicity states of the neutrino necessary to construct a Dirac mass must have interactions strong enough to evade the astrophysical bound from SN 1987A, but weak enough to avoid violating the bound from primordial nucleosynthesis.

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In 1985, Simpson¹ reported an anomaly in the shape of the Kurie plot for tritium β decay. He interpreted this anomaly as evidence for a small (few %) component of a 17 keV mass eigenstate in the weak-interaction eigenstate of the electron neutrino. Since then, additional experiments involving the β -decay of ^3H ,² ^{35}S ,³ ^{63}Ni ,⁴ ^{14}C ,⁵ and ^{55}Fe ⁶ have been performed, with some supporting and some refuting his hypothesis. While the experimental situation is far from clear, the evidence presented by Hime and Jelley³ for ^{35}S makes a strong case for a 17 keV neutrino-mass eigenstate in the electron-flavor eigenstate at about the 1% level ($\sin^2 \theta = 0.0085$). In this *Letter* we will discuss the mine field of astrophysical and cosmological constraints that must be negotiated by those building particle physics models to accommodate such a neutrino.

Accelerator limits to $\nu_\mu \longleftrightarrow \nu_e$ oscillations preclude the possibility that the 17 keV mass eigenstate is associated with ν_μ .⁷ Since precision determinations of the width of the Z^0 allow for only three neutrinos of mass less than 45 GeV ($\simeq m_Z/2$), the 17 keV neutrino must be predominately ν_τ . Furthermore, the absence of neutrinoless double- β decay in several isotopes limits the size of the Majorana mass of any neutrino-mass eigenstate that mixes with the electron weak-interaction eigenstate:⁸ $m_M \lesssim 3\text{eV} \sin^2 \theta$. For a 17 keV neutrino this precludes a Majorana mass unless $\sin^2 \theta \lesssim 2 \times 10^{-4}$. On the face of it then, we are presented with a 17 keV tau-neutrino Dirac mass eigenstate.⁹

A Dirac neutrino mass requires four helicity states, while only two are present in the standard model. (The four degrees of freedom of a Dirac neutrino are: ν_- , ν_+ , and their CP -conjugate states $\bar{\nu}_+$, and $\bar{\nu}_-$.¹⁰) If a neutrino species is massive, then the helicity eigenstates (ν_+ , ν_-), the eigenstates of a freely propagating neutrino, do not coincide with the chirality eigenstates (ν_L , ν_R), the eigenstates of the weak interaction. Roughly speaking, a highly relativistic ν_- (ν_+) has projection of order unity onto ν_L (ν_R) and projection of order $m_\nu/2E_\nu$ onto ν_R (ν_L). This means that ν_- and $\bar{\nu}_+$ have ordinary weak interactions, while the “wrong”-helicity states ν_+ and $\bar{\nu}_-$ are almost inert (in the context of electroweak theory). *Almost* inert, because their small projections onto ν_L and $\bar{\nu}_R$ lead

to interactions with cross sections that are approximately a factor $(m_\nu/2E_\nu)^2$ smaller than ordinary weak interactions.

Having set the stage we will recite the litany of astrophysical and cosmological arguments that bear on the existence and properties of a 17 keV Dirac neutrino. In brief, to avoid “overclosing” the Universe, such a neutrino must be endowed with interactions beyond those of the electroweak theory, in order to decrease its relic abundance through decay or annihilation. Even more importantly, there are complementary constraints based upon the cooling of the newly born neutron star associated with SN 1987A and primordial nucleosynthesis: To avoid excessive shortening of the duration of the neutrino burst from SN 1987A the wrong-helicity states of the 17 keV neutrino must have interactions that are roughly weak in strength so that they become trapped in the proto-neutron star interior; however, interactions of sufficient strength to accomplish this will in general populate the wrong-helicity states in the early Universe and lead to a violation of the stringent nucleosynthesis limit to the number of neutrino species.

Relic density: First consider the mass density contributed by a 17 keV neutrino. To begin, we will assume that it has only the interactions of the electroweak theory. In this case the calculation its relic mass density is a textbook example:¹¹ The interactions of a neutrino species “freeze out” (interaction rate Γ becomes less than the expansion rate $H \simeq 1.67\sqrt{g_*}T^2/m_{\text{Pl}}$) when the temperature is a few MeV; a 17 keV neutrino species is still relativistic at this time so its abundance is equal to that of a massless neutrino species. (Here g_* counts the number of relativistic degrees of freedom and $m_{\text{Pl}} = 1.22 \times 10^{19}$ GeV.) After its interactions freeze out, its abundance per comoving volume (or equivalently, its abundance relative to the entropy density, $Y \equiv n_\nu/s \simeq 0.0388$) remains constant. The present contribution to the mass density (expressed as the fraction of critical density, Ω_{17}) is

$$\Omega_{17}h^2 \simeq (s_0 Y)17 \text{ keV}/1.05 \times 10^4 \text{ eV cm}^{-3} \simeq 187; \quad (1)$$

where the present value of the Hubble parameter $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$, the present entropy density $s_0 = 2970 \text{ cm}^{-3}$, and $1.05h^2 \times 10^4 \text{ eV cm}^{-3}$ is the critical density. (For the moment we are ignoring the wrong-helicity degrees of freedom, because as discussed below, with only the standard electroweak interactions they are not populated.)

If the 17 keV neutrino is stable and has the standard interactions, its relic abundance “overcloses” the Universe by a wide margin (based upon the age of the Universe, $\Omega_{\text{TOT}} h^2 \lesssim 1$). There are three ways to mitigate this problem: (i) dilute the neutrino-to-entropy ratio by entropy production; (ii) decrease the neutrino abundance through additional annihilation processes; or (iii) diminish the neutrino abundance by decay. The last two possibilities require neutrino interactions beyond those in the standard electroweak theory. Of course, the very existence of a mass for a neutrino species implies that neutrinos must have some new interactions. If the relic abundance is reduced by entropy production or annihilation by about a factor of 200, then 17 keV neutrinos could provide closure density. If so, they would behave either as warm or cold dark matter.¹²

(i) Entropy production: An increase in the entropy by a factor of 200 (e.g., through massive-particle decays or a phase transition) after the 17 keV neutrino freezes out would resolve the abundance dilemma. The entropy injection could not have taken place after nucleosynthesis, as nucleosynthesis constrains any such entropy production to be less than a factor of 30.¹³ On the other hand, if the entropy production took place before nucleosynthesis, it would have to occur *after* the 17 keV neutrino freezes out ($T \simeq 4 \text{ MeV}$) and *before* the electron-neutrino freezes out ($T \simeq 2 \text{ MeV}$), otherwise electron neutrinos would also be diluted—which is bad as the ^4He yield is very sensitive to the electron-neutrino abundance.¹⁴ (Because of charged-current interactions e -neutrinos decouple slightly later than μ - and τ -neutrinos.¹⁴) While it is possible that the desired entropy production could have occurred just prior to—or even part way through—nucleosynthesis, without interfering with the outcome, this seems like a longshot.

(ii) Enhanced annihilation: The relic abundance of a stable species whose interactions

freeze out while it is nonrelativistic is given by¹¹

$$Y \simeq \frac{3.8(n+1)x_F}{\sqrt{g_*}m_\nu m_{\text{Pl}} \langle \sigma_A |v| \rangle}; \quad (2)$$

where n parameterizes the temperature dependence of the thermal average of its total annihilation cross section, $\langle \sigma_A |v| \rangle \propto T^n$, and x_F is related to the freeze-out temperature by $x_F = m_\nu/T_F$. In order that the present abundance be acceptable, Y must be less than about 2.1×10^{-4} , corresponding to $x_F \gtrsim 10$. This leads to a lower limit to the annihilation cross section, evaluated at a temperature of about 1 keV: $\langle \sigma_A |v| \rangle \gtrsim 2(n+1) \times 10^{-37} \text{ cm}^2$. For comparison, the annihilation cross section due to electroweak interactions is $\langle \sigma_A |v| \rangle \simeq G_F^2 m_\nu^2 / 2\pi \simeq 2.5 \times 10^{-48} \text{ cm}^2$, some 11 orders of magnitude too small!

(iii) Decay: If the 17 keV neutrino is unstable and decays into relativistic particles, whose energy density red shifts as $(1+z)^{-4}$ rather than $(1+z)^{-3}$, the energy density of its daughter products is today a factor of $(1+z_D)$ *less* than that of a stable 17 keV neutrino.¹⁵ Here, z_D denotes the red shift of its decay epoch, which must be greater than about 190. This in turn implies that the lifetime of the 17 keV neutrino must be less than the age of the Universe at red shift z_D : $t_U(z_D \sim 190) \sim 4 \times 10^{12} (\Omega_0 h^2)^{3/2} \text{ sec}$.¹⁶

In the context of the electroweak theory a massive neutrino can decay: $\nu_\tau \rightarrow \nu_e \gamma, \nu_\mu \gamma$, with a mean lifetime $\tau_\nu = 512\pi^4 \alpha^{-1} G_F^{-2} I^{-2} m_\nu^{-5} \sin^{-2} 2\theta \sim 4 \times 10^{22} \text{ sec}$ for $m_\nu = 17 \text{ keV}$ and $\sin^2 \theta = 0.0085$.¹⁷ (Here $I = (m_\tau^2/m_W^2)[\ln m_W^2/m_\tau^2 + \mathcal{O}(1)]$ is the GIM suppression factor.) Such a lifetime is many orders of magnitude too long to resolve the cosmological woes of a 17 keV neutrino; moreover, it would lead to an unacceptably large photon flux.^{10,18,19} In particular, the absence of gamma rays from SN 1987A constrains the radiative lifetimes of all three neutrino species:¹⁹ $\tau_\nu \gtrsim 8.4 \times 10^{17} B_\gamma \text{ sec eV}/m_\nu \simeq 4.9 \times 10^{13} B_\gamma \text{ sec}$ (for the 17 keV neutrino), where B_γ is the branching ratio to all decay modes that produce a photon. This bound conflicts with the desired lifetime, $\tau_\nu \lesssim 4 \times 10^{12} \text{ sec}$, if $B_\gamma \gtrsim 0.1$; for the process being considered $B_\gamma = 1.0$.

New interactions can allow the 17 keV neutrino to decay more rapidly and without

producing γ 's. For example, suppose that there are horizontal interactions characterized by a symmetry-breaking scale f .²⁰ On dimensional grounds, the lifetime for the process $\nu_\tau \rightarrow \nu_e \phi$, $\nu_\mu \phi$ (ϕ is a massless, inert Goldstone boson) is $\tau_\nu \sim 8\pi f^2/m_\nu^3 \sim 3 \times 10^7 \text{ sec} (f/10^8 \text{ GeV})^2$. If the scale f is less than about 10^8 GeV , the lifetime will satisfy even the more stringent cosmological constraint discussed next. In any case, one must check to make sure that the branching ratio to any radiative decay mode is very small to avoid the overproduction of diffuse photon radiation.^{18,19}

There is another cosmological consideration. If the 17 keV neutrino decayed at a red shift of 190, then the Universe has been radiation dominated since $z \sim 190$. Since linear density perturbations do not grow while the Universe is radiation dominated, the 17 keV neutrino would have a deleterious effect upon structure formation. To be sure, the details of structure formation are not yet fully understood; however, it has been argued on this basis that the lifetime of a 17 keV neutrino must be less than about 1 yr, so that the Universe was matter dominated during its recent past.²¹ The lifetime constraint based upon the age of the Universe is hard and fast; the more stringent constraint based upon structure formation is worthy of careful consideration, although it is not as secure.

We now describe the astrophysical/cosmological quandary that arises because the 17 keV neutrino must have a Dirac mass. There are two situations where the additional, wrong-helicity states can play an important role: SN 1987A and primordial nucleosynthesis. To be consistent with the neutrino bursts detected from SN 1987A the wrong-helicity states must have new interactions that are roughly weak in strength. However, such interactions lead to a violation of the primordial nucleosynthesis constraint!

SN 1987A: The bulk of the binding energy released in the formation of the neutron star associated with SN 1987A was carried away by thermal neutrinos. Because of the high temperatures (up to 70 MeV) and densities (up to $8 \times 10^{14} \text{ g cm}^{-3}$) in the nascent neutron star, neutrinos are "trapped" within the core and radiated from a "neutrino sphere" ($T \sim 5 \text{ MeV}$, $\rho \sim 10^{12} \text{ g cm}^{-3}$). The "spin-flip" interactions of the standard electroweak theory

(e.g., $\nu_- e^- \rightarrow \nu_+ e^-$) transmute ν_- to ν_+ deep inside the nascent neutron star, with a cross section $\sigma \sim G_F^2 m_\nu^2$.²² The wrong-helicity states can efficiently cool the core because they have an interaction cross section which is much weaker than the normal-helicity states: Once created, the wrong-helicity states stream out, carrying off energy and thereby accelerating the cooling of the core. Burrows and Gandhi have carefully studied the cooling effect of Dirac neutrinos on the neutrino flux from SN 1987A.²³ Based upon detailed numerical modeling of the cooling and the response of the IMB and KII detectors, they conclude that a Dirac neutrino mass of greater than 14 keV would lead to an unacceptable shortening of the detected neutrino bursts (to less than 1 sec in the IMB detector and less than 1.5 sec in the KII detector). The limit $m_\nu < 14$ keV appears to be a very conservative one, and a 17 keV mass Dirac neutrino is seriously at odds with it.

There is a way around this bound: A new interaction could prevent the wrong-helicity states from free-streaming out of the core. This new interaction could either convert the wrong-helicity neutrino to the normal-helicity state, or could “cool” the wrong-helicity neutrinos emitted deep in the core by elastic scatterings with the other particles present (electrons, positrons, protons, neutrons, and proper-helicity neutrinos).²⁴ If the mean free path for such processes is smaller than the size of the core, the wrong-helicity states will be trapped, and ν_+ and $\bar{\nu}_-$ will be radiated from a “wrong-neutrino sphere,” whose location and temperature are determined by the strength of the new interactions. To estimate the strength necessary, we follow the simple—but accurate—analytic model used previously to study axion emission and trapping.²⁵

The wrong-neutrino sphere is the surface beyond which a wrong-helicity neutrino has a probability of 2/3 to interact again: $2/3 = \int_r^\infty dr/l$, where $l = 1/n\langle\sigma|v|\rangle$ is the mean-free path for interaction, which depends upon the interaction cross section σ and the number density of targets n . Provided that the temperature at the wrong-neutrino sphere is less than about 10 MeV, the effect of wrong-helicity neutrinos on the neutrino burst should be acceptable.^{24,25} We parameterize the wrong-helicity-state interaction cross section as

$\langle\sigma|v|\rangle = \sigma_0(G_F 10 \text{ MeV})^2 T_{10}^\delta$ where $T_{10} = T/10 \text{ MeV}$, the factor, $(G_F 10 \text{ MeV})^2 \simeq 5 \times 10^{-42} \text{ cm}^2$, is a typical weak-interaction cross section, and δ parameterizes the temperature dependence. Using the model and procedures described in Ref. 25, we find that sufficient trapping of the wrong-helicity states requires: $\sigma_0 \gtrsim 0.01$ (if the new interactions are with nucleons or electrons); or $\sigma_0 \gtrsim 1$ (if the new interactions are with neutrinos). Moreover, our constraint to the cross section in the case of electrons is a very conservative one as we have neglected electron degeneracy which suppresses interactions with electrons.

Nucleosynthesis: As is well appreciated, primordial nucleosynthesis can be used to place a limit to the number of ultrarelativistic degrees of freedom that are in thermal equilibrium when the temperature of the Universe was about 1 MeV. Stated in terms of the equivalent number of light (mass $\ll 1 \text{ MeV}$) neutrino species, the current bound is $N_\nu \leq 3.4$.²⁶ If the wrong-helicity states of the 17 keV neutrino were thermally populated, then the neutrino count would be 4. The important question then is whether or not the interactions of the wrong-helicity state are sufficiently strong to bring them into equilibrium?

First consider electroweak interactions. The temperature at which spin-flip interactions become ineffective ($\Gamma < H$) is $T_F \sim 100 \text{ GeV} (17 \text{ keV}/m_\nu)^2$.²⁴ If a species decouples at a temperature greater than that of the quark/hadron transition ($T \sim 300 \text{ MeV}$), its abundance will be greatly reduced by the entropy transfer from the quark/gluon plasma to the hadronic degrees of freedom, and it will not contribute significantly to the neutrino count. Thus, in the absence of new interactions, the wrong-helicity state neutrinos will not add significantly to the neutrino count.

However, the new interactions that are needed to trap wrong-helicity neutrinos in SN 1987A change that situation dramatically. Typically there is a crossing symmetry between the scattering cross section responsible for trapping ν_+ and $\bar{\nu}_-$, (e.g., $\nu_+ X \leftrightarrow \nu_- X$), and the creation/annihilation cross section responsible for populating the wrong-helicity state in the early Universe, (e.g., $\nu_+ \bar{\nu}_+ \leftrightarrow X \bar{X}$). Comparing the interaction rate $\Gamma \simeq n\langle\sigma|v|\rangle$ for the new interactions that would trap wrong-helicity neutrinos in SN 1987A with the

expansion rate, one finds $\Gamma/H \sim 50\sigma_0(T/10\text{ MeV})^{\delta+1} \gtrsim 0.5(T/10\text{ MeV})^{\delta+1}$. The import of this is clear: Irrespective of the temperature dependence of the new interactions (i.e., δ), if they are strong enough to trap the wrong-helicity state neutrinos in SN 1987A, they are potent enough to populate the wrong-helicity state neutrinos after the quark/hadron transition and before nucleosynthesis, ensuring that the wrong-helicity states contribute a full unit to the neutrino count. (They might also populate the wrong-helicity states of e - and μ -neutrinos, or additional light degrees of freedom associated with the new interactions, further exacerbating the problem.) That this occurs should not be too surprising: The temperatures in both situations are similar, and the interaction strength required, roughly weak, is comparable.

On the face of it then, the 17 keV neutrino is on the horns of a dilemma: Because of the complementarity of the SN 1987A and nucleosynthesis bounds, it appears that they cannot both be satisfied by invoking new interactions. There may be ways out of the predicament. In discussing the thermalization of wrong-helicity state neutrinos in the early Universe we have assumed that the target particles whose interactions lead to their thermalization have an abundance comparable to photons; while true for neutrinos and electrons, it is not true for nucleons—their abundance is only about 10^{-10} that of photons. If the new interactions responsible for trapping the wrong-helicity neutrinos in the neutron star involve only nucleons, one could possibly evade both bounds. Another possibility is the rapid decay of wrong-helicity neutrinos into proper-helicity neutrinos and an inert particle. Provided that the decay occurs inside the neutrino sphere ($r \lesssim 3 \times 10^6$ cm) the energy carried off by wrong-helicity neutrinos is returned (whether or not this transport of energy from deep inside the core to near the neutrino sphere has other deleterious effects remains to be seen). This solution requires a very short lifetime for the 17 keV neutrino: $\tau \lesssim 10^{-7}$ sec. A third possibility is that the scattering of the wrong-helicity neutrinos in the core is not simply related to the annihilation cross section necessary to populate the wrong-helicity state in the early Universe. This is difficult to arrange.

To conclude, the properties of a 17 keV Dirac neutrino are strongly constrained by astrophysical and cosmological arguments. In particular, it seems to be caught between astrophysics—the SN 1987A constraint requires that it have additional interactions—and cosmology—the primordial nucleosynthesis constraint precludes it from having such additional interactions.

If a 17 keV Dirac neutrino does indeed exist its importance cannot be overstated. Not only would it be quite a surprise from the perspective of current prejudices in theoretical particle physics, but it would also be difficult to accommodate astrophysically and cosmologically. In short, it will provide a good test for the creativity of both theoretical astrophysicists and particle physicists!

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